Diesel particulate exposures in underground mines

R. A. Haney

Abstract —*The Mine Safety and Health Administration (MSHA) has conducted studies both in coal and non-coal mines to evaluate methods for sampling diesel particulates in underground mines. The agency is investigating size separation techniques to distinguish between diesel particulate and respirable coal mine dust. Additionally, ashing techniques have been used to distinguish diesel particulate from mineral dust in metal and non-metal mines.*

As part of these studies, personal exposures to diesel particulate for various mining occupations have been measured. This paper describes the measurement techniques and summarizes the exposure levels for various underground mining operations.

Introduction

During the past decade there has been an increase in the use of diesel-powered equipment in both underground coal and non-coal mines. Along with the increased usage there have been increased concerns regarding potential health effects of long- and short-term exposure to diesel exhaust. Long-term health effects are associated with inhalation and deposition of diesel particulate in the lungs. Short-term health effects are associated with inhalation and absorption of gaseous contaminants into the blood and irritation of mucous membranes.

The National Institute for Occupational Safety and Health (NIOSH) has recommended that whole diesel exhaust be regarded as a potential occupational carcinogen (NIOSH, 1988). As a result, in the "Report of the Mine Safety and Health Administration Advisory Committee on Standards and Regulations for Diesel-Powered Equipment in Underground Coal Mines" (US Department of Labor, 1988), it was recommended that the Secretary of Labor set in motion a mechanism whereby a diesel particulate standard could be set. One of MSHA's efforts has been to develop and evaluate instrumentation and methods to distinguish diesel particulate from mineral dust. As part of this effort, comparative measurements with various particulate sampling devices have been obtained of employee exposure to diesel particulates for various occupations in both coal and noncoal mining operations.

The purpose of this paper is to summarize the exposure levels to diesel particulate that were measured and to describe and evaluate the accuracy and precision of the sampling instrumentation and analytical methods used. Exposure level data will provide some background information on diesel particulate exposures that currently exist in the mining industry.

Table 1 — Calculation of diesel particulate concentration from ashing method.

Diesel plus mineral dust		
Filter Pre-Weight	12.572	mg
Filter post-weight	13.475	mg
Mass of dust (1)	0.903	mg
Mineral dust		
Filter pre-weight	8.584	mg
Filter plus ash post-weight	9.057	mg
Mass of ash and filter	0.473	mg
Mass of ashed filter	0.014	mg
Mass of mineral dust (2)	0.459	mg
Diesel particulate		
Mass of dust (1)	0.903	mg
Mass of mineral dust (2)	0.459	mg
Mass of diesel particulate	0.444	mg
Sampling parameters		
Flow rate	1.7	Lpm
Sample time	480	min
Volume sampled	0.816	m^3
Dust concentrations		
Diesel particulate	0.54	mg/m^3
Respirable dust	1.11	mg/m^3
% Diesel particulate	49.17%	

Sampling and analytical methods

Metal and non-metal mining operations

Distinguishing between diesel and non-diesel particulates in non-carbonaceous metal and non-metal mining operations does not pose the analytical problems associated with distinguishing between diesel particulate and a carbonaceous (coal) dust. For a metal and non-metal mining operation, respirable dust samples are collected on a preweighed PVC filter. The samples are collected at 1.7 Lpm with a 10 mm (0.4 in) nylon cyclone as a preseparator. The filters are then post-weighed to determine the mass of the respirable dust which includes both diesel particulate and mineral dust. All weighings are to 0.001 mg on an analytical microbalance.

The filters containing the dust are then placed in beakers in a low-temperature asher and the diesel particulate material ashed at 120°C (248°F) in an oxygen-enriched plasma. For samples containing soluble mineral dust, the filters are ashed onto a preweighed stainless steel plate. For non-soluble minerals, the ash is rinsed with alcohol from the beakers and refiltered onto a preweighed filter. Filters or stainless steel plates are then post-weighed to determine the mass of the ash or mineral dust. This mass is corrected for the mass of an ashed filter. A direct on-filter analysis can be made for either soluble or non-soluble minerals by collecting the sample on a silver membrane filter and ashing the sample at 400°C (752°F) in a muffle furnace. The mass of diesel particulate is determined by taking the difference between the composite respirable dust mass and the mass of the mineral ash. Diesel particulate concentrations are determined by dividing the diesel particulate mass by the volume of air sampled.

An example of these calculations are given in Table 1. Control tests on ashed respirable mineral dust not containing diesel particulates agreed within ±0.05 mg with the initial unashed mass determination.

R.A. Haney, member SME, is supervisory mining engineer, Mine Safety and Health Administration, Pittsburgh, PA. SME preprint 90-40, SME Annual Meeting, Feb. 26 - March 1, 1990, Salt Lake City, UT. Manuscript October 1989. Discussion of this paper must be submitted, in duplicate, prior to May 31, 1992.

Samples were collected at four metal and non-metal mining operations. Operations sampled included two single-level limestone mines, one single-level salt mine and one-multiple level metal mine. Area samples were collected on the working sections and in underground shop areas; full-shift personal samples were collected on underground personnel. The single-level mines utilized diesel front-end loaders or diesel shuttle cars to transport material to conveyer belts. The multiple-level mine used diesel front-end loaders and ore trucks to transport ore to a hoisting facility.

Coal mining operations

The chemical separation of respirable coal mine dust from diesel particulate has not been generally successful due to the similar chemical characteristic of the two materials. Research has shown that in non-dieselized coal mining operations, the respirable dust has a mono-modal size distribution with less than 10% of the dust in the submicrometer size range. In dieselized underground coal mines, the aerosol has a bi-modal size distribution with the second mode occurring in the submicrometer size range. The intersection of these two modes occurs at approximately 0.80 μm. Aerosol particles greater than 0.80 μm in aerodynamic diameter are therefore considered mineral dust. Particles smaller than 0.80 μm are considered diesel particulates (Rubow, 1988). As a result, a physical size separation technique, utilizing single-stage aerosol impactors, has been developed.

Tests were conducted in coal mines on two different single-stage impactors: a prototype single-jet impactor designed and built by MSHA (MSHA impactor) (Haney, 1989) and a multiple-jet impactor designed and built by the University of Minnesota under a grant from the US Bureau of Mines' Minerals Industry Generic Dust Center Program (UMinn impactor) (Cantrell, 1990). Each impactor was operated at a 2.0 Lpm flow rate with a 10 mm (0.4 in) nylon cyclone preseparator. For both impactors, dust greater than 0.80 μm is impacted and retained on a greased plate. The dust less than 0.80 μm bypasses the impaction plate and is retained on a filter.

Both the impaction plate and the final filter were pre- and post-weighed to 0.001 mg. In this manner the samplers could be used to determine both the diesel particulate and the respirable coal mine dust concentrations. The diesel particulate concentration was determined by dividing the diesel particulate mass by the volume of air sampled. The Mine Research Establishment (MRE) equivalent respirable coal mine dust concentration was determined by multiplying the sum of the impactor plate mass and filter mass by 1.38 then dividing by the volume of air sampled.

For diesel particulate exposure determinations in coal mines, sampling packages, consisting of single-stage impactors and respirable coal mine dust samplers, were placed in the section intake (outby the last intake stopping), in the haulageway (inby the section dump point) and on various pieces of face equipment.

Face equipment sampled included the continuous miner and the diesel haulage vehicles. Sample packages were operated either on section or portal-to-portal. Table 2 gives an example of the diesel particulate calculations based on impactor samples.

Samples were collected in five coal mines using diesel equipment. One mine used only diesel outby equipment. The other four mines used diesel face haulage as well as diesel outby equipment. Each diesel section used two Jeffery Model 4110 diesel Ramcars. In addition to particulate measurements, section air quantities and diesel particulate generation rates were also determined.

An additional sampling package consisting of two respirable dust samplers; two total dust samplers; five MSHA impactors; five UMinn impactors; and two Anderson 290 Series, Marple Personal Cascade Impactors Model 298 (Marple 298) was used to sample the section return. The Marple 298 is an eight-stage impactor with a final filter and cut points at 0.5, 0.9, 2.0, 3.5, 6.0, 10.0, 15.0, and 21.0 μm when operated at a flow rate of 2.0 Lpm. These samples were collected to determine accuracy and precision of the two single-stage impactors. The samples were collected in the section return so that a range of impactor loadings could be attained by adjusting the sampling times. Return sample results were used to calculate section diesel particulate generation rates.

Table 2 — Calculation of diesel particulate concentration from impactor samples.

Diesel particulate		
Filter pre-weight	265.362	mg
Filter post-weight	265.866	mg
Mass of diesel particulate	0.504	mg
Impaction plate		
Plate pre-weight	475.964	mg
Plate post-weight	476.588	mg
Mass of dust	0.624	mg
Total mass of dust	1.128	mg
Sampling parameters		
Flow rate	2.0	Lpm
Sampling time	480	min
Volume sampled	0.960	m³
MRE conversion	1.38	
Dust concentrations		
Diesel particulate	0.52	mg/m³
Respirable dust (MRE)	1.62	mg/m³
% Diesel particulate	32.38%	

Results and discussion

Table 3 gives the results of respirable dust and diesel particulate measurements made in underground metal and non-metal mines. These samples were analyzed using the ashing technique. Mines A, B, and C were single-level room and pillar mines. Mine D was a multi-level ore mine. Respirable dust levels ranged from 0.38 mg/m^3 to 2.68 mg/m^3. Diesel particulate constituted 48% to 88% of the sample giving diesel exposure levels of .26 to 2.36 mg/m^3.

The effect of series ventilation on contaminant buildup is shown in the samples collected in mines A and B. Successive areas in the mine have increasing exposure to diesel particulates because the return of one section becomes the intake for the next section. The samples collected in mines C and D show some

Table 3—Results of diesel particulate and respirable dust samples collected in underground metal and non-metal mines.

Sample	Mine A	Mine B	Mine C	Mine D Unit 1	Mine D Unit 2
	Unit 1	Shop	Loader	Tram	Tram
Respirable dust, mg/m³	0.38	1.20	0.41	1.04	1.31
Diesel particulate, mg/m³	0.26	0.79	0.30	0.68	0.96
% Diesel particulate	68.42	65.83	73.17	65.38	73.28
	Unit 2	Unit 1	Euclid	Ore car	Ore car
Respirable dust, mg/m³	0.99	2.18	0.83	0.64	0.85
Diesel particulate, mg/m³	0.75	1.28	0.50	0.31	0.56
% Diesel particulate	75.75	58.71	60.24	48.43	65.88
			Truck	Ore Car	Scoop
Respirable dust, mg/m³			0.84	0.87	2.68
Diesel particulate, mg/m³			0.59	0.42	2.36
% Diesel particulate			70.23	48.27	88.06

variation in the on-section exposures. The operators of scoops and trams had the highest exposures to both respirable dust and diesel particulate. This equipment is normally operated in the more confined areas of the mine where lower air quantities are available for dilution of contaminants.

Table 4 gives results of respirable dust and diesel particulate measurements made in underground coal mines using diesel equipment. These samples were collected with the single stage impactors. The values represent average exposures for two to five shifts sampled. Mine A only used diesels for outby transportation of workers and supplies. Mines B, C, D and E used diesel equipment for face haulage as well as outby transportation of workers and supplies.

Intake dust levels ranged from 0.13 to 0.58 mg/m^3. Intake diesel particulate levels ranged from 0.04 to 0.29 mg/m^3 or 30% to 50% of the respirable coal mine dust concentration. Face worker respirable dust exposures ranged from 0.73 mg/m^3 to 2.85 mg/m^3. Worker exposure to diesel particulate ranged from 0.18 mg/m^3 to 1.00 mg/m^3. The diesel particulate sample collected in the haulageway agreed to within 0.12 mg/m^3 of the section workers' exposure.

On each section sampled, the range between highest and lowest exposure to diesel particulate was less than 0.17 mg/m^3. This indicates the uniform concentration of diesel throughout the face area. A comparison of diesel exposure at the different mines shows the influence of air volume to dilute the diesel particulate. The higher the section air volume, the lower the exposure to diesel particulate.

Figure 1 shows a typical plot of the size distribution for simultaneous Marple 298 impactor measurements collected in the section return. The DC/DLOG DP (change in concentration (DC) per log of the particle size interval (DP)) scale on the "Y" axis is used to provide a visual representation of the concentration per unit size. The changes in concentration in the size ranges less than 0.8 µm are attributed to diesel particulates.

The face area diesel particulate generation rate was estimated by multiplying the return airflow by the difference of the return and intake diesel particulate concentrations. The value 35,315 converts cubic feet to cubic meters and milligrams to grams.

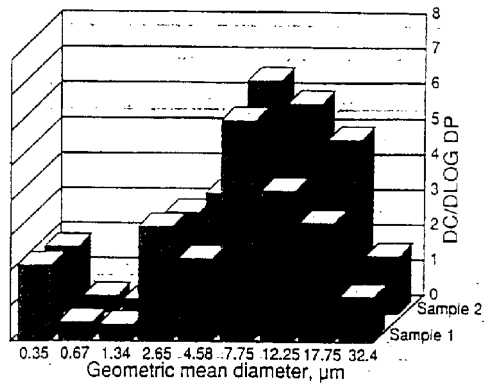

Fig. 1—Particle size distribution of simultaneous Marple 298 impactor measurements in section return of underground coal mine with diesel face haulage equipment.

$$G = (R-I) * Q/35{,}315$$

where: G = Diesel particulate generation rate, g/min; R = Return diesel particulate concentration, mg/m^3; I = Intake diesel particulate concentration, mg/m^3; and Q = Return airflow, cfm.

The results of this determination for each coal mine are also shown in Table 4. The diesel particulate generation rates ranged from 0.53 to 1.30 g/min. For approval of diesel-powered face equipment in underground coal mines, MSHA typically requires 100% of the nameplate air quantity for the first diesel unit, 75% for the second unit, and 50% for each additional piece of equipment. For two diesel haulage vehicles, each with a nameplate air quantity of 4.1 m^3/s (8700 cfm), an air volume of 7.2 m^3/s (15,255 cfm) would be required. This 7.2 m^3/s would dilute the above diesel particulate generation rates to between 1.23 and 3.02 mg/m^3. An air quantity of 16.7 m^3/s (35,315 cfm) would be required to dilute a diesel particulate generation rate of 1.0 g/min to 1.0 mg/m^3.

The paired data from three of the coal mine studies were analyzed to determine how well the MSHA and UMinn diesel particulate samplers performed as respirable samplers and how well the diesel determinations compared to each other. An analysis was conducted on over 50 paired respirable and impactor samples for respirable concentrations ranging from approximately 0.4 to 4.0 mg/m^3 and diesel particulate concentrations ranging from 0.10 to 1.10 mg/m^3. A "t" test performed on this data showed that at the 5% significance level, the average of the ratios determined between either the MSHA or the UMinn impactor respirable dust determination and the standard respirable dust measurement was not different than unity (the ratio expected for comparative measurements with similar sampling devices). Additionally, the "t" test showed that the difference between the diesel particulate determination made with the two impactors was not significant. The impactor respirable measurements agreed to within 25% of the standard respirable measurements and on the average the diesel particulate measurements agreed within to 0.05 mg/m^3 of each other.

Table 4—Results of diesel particulate and respirable dust samples collected in underground coal mines.

Location	Mine A	Mine B	Mine C	Mine D	Mine E
Intake					
Respirable dust, mg/m^3	0.58	—	0.36	0.13	0.41
Diesel particulate, mg/m^3	0.29	—	0.14	0.04	0.19
% Diesel particulate	50.00	—	38.88	30.76	46.34
Haulageway	-				
Respirable dust, mg/m^3		—	0.68	1.95	1.58
Diesel particulate, mg/m^3		—	0.14	0.95	0.72
% Diesel particulate		—	20.58	48.71	45.57
Continuous miner					
Respirable dust, mg/m^3		1.55	0.81	—	—
Diesel Particulate, mg/m^3		0.56	0.18	—	—
% Diesel particulate		36.12	22.22	—	—
Haulage vehicle					
Respirable dust, mg/m^3		1.34	0.73	2.08	2.52
Diesel particulate, mg/m^3		0.72	0.21	1.00	0.74
% Diesel particulate		53.73	28.76	48.07	29.36
Haulage Vehicle					
Respirable dust, mg/m^3		1.35	1.00	2.06	2.85
Diesel particulate, mg/m^3		0.55	0.26	0.93	0.67
% Diesel particulate		40.74	26.00	45.14	23.50
Section airflow, cfm	45,000	50,000	130,000	34,000	45,000
(m^3/s)	(21.2)	(23.6)	(61.3)	(16.0)	(21.2)
Diesel particulate					
generation rate, g/min	—	1.01	0.53	0.73	1.30

Results of the respirable and diesel

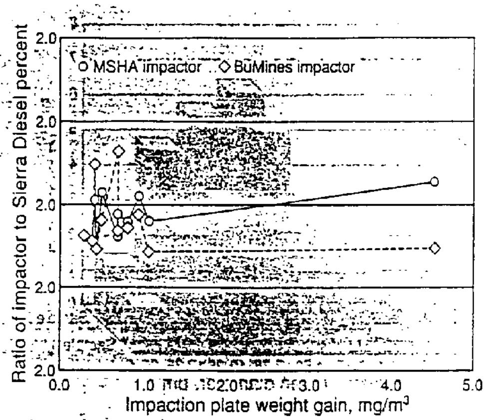

Fig. 2—Ratios of MSHA and UMinn impactor diesel percentage to Marple 298 diesel percentage vs. impaction plate weight gain.

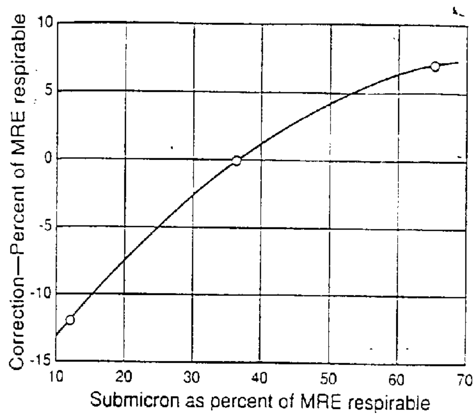

Fig. 3—Correction to the diesel particulate measurement for percentage of sub-0.8μm dust present.

particulate samples collected in the section return were analyzed to determine accuracy and precision of the instruments. Accuracy was determined by comparing the ratio of the MSHA and UMinn impactor diesel percentages to the Marple 298 diesel percentages. The Marple diesel percentages were obtained by adding the final filter and the 0.5 μm impaction plate masses. Since both of the instruments had calculated cut points less than the Marple 298, this value should be less than 1.0. A plot of the ratio of MSHA and UMinn impactor diesel percentage to Marple 298 diesel percentage versus impaction plate weight gain is shown in Figure 2. For the MSHA impactor this value ranged from 0.81 to 1.10 for impaction plate weight gains less than 3.0 mg. For impaction plate weight gains greater than 3.0 mg the ratio of MSHA to Marple 298 impactor was greater than 1.10, indicating an impaction plate overloading. For impaction plate weight gains greater than 1.0 mg the ratio of UMinn impactor to Marple 298 was less than 1.0, indicating that the UMinn impactor did not overload at impaction plate loadings up to 4.5 mg. The increased variability of both impactor measurements at the lower plate loadings may be due to low plate and filter weight gains.

Precision of the instruments was determined from the standard deviation and coefficient of variation of the grouped measurements collected in the section return. Analysis was performed on 16 groups of samples. For all instruments the standard deviation was less than 30% of the average determination. The standard deviation of the grouped diesel particulate measurements ranged from +0.03 to +0.19 mg/m³. The standard deviation of the diesel percentage measurements ranged from +0.71 to +30%.

Both the ashing and impactor methods for determining diesel particulates are gravimetric types of analysis. While these methods may be suitable for determining diesel particulate levels that currently exist, additional evaluation needs to be performed to determine the lower limit of this method for measuring diesel particulate. Gravimetric methods have not generally been used to determine particulate concentrations less than 0.10 mg/m³.

In addition to the limitations of gravimetric methods, the impactor may be subject to interference from submicrometer mineral dust. Tests conducted with the MSHA and UMinn impactors in coal mines not using diesel-powered equipment, showed the sub-0.8 μm particulate contribution to be approximately 12% of the respirable dust level for each instrument. Additionally, tests conducted by Rubow indicate that when water scrubbers are used on diesel equipment, approximately 8% of the diesel aerosol is greater than 0.8 μm. As a result, measurements made with a impactor could either over estimate or under estimate the diesel concentration, depending on the percent diesel present in the mine dust. Figure 3 shows the approximate correction to the diesel particulate measurement for various percentages of sub-0.8 μm dust present. Table 4 indicates that when diesel haulage vehicles are used, the percent diesel is generally between 25% and 55%. In this range, the correction as seen from Figure 3, would be less than +0.05 mg/m³ per mg/m³ of respirable coal mine dust.

The diesel particulate concentrations shown in Tables 3 and 4 represent exposure levels that exist with good mining practices. There was no attempt to isolate high exposures that might occur where poor mining practices are employed. Controls that are currently available for reducing exposure to diesel particulate include ventilation, engine maintenance and for coal mines, wet exhaust scrubbers.

Summary

Two methods have been successfully used to determine diesel particulate levels in underground mines. An ashing method has been used in non-coal mines. A size separation method has been used in coal mines. Both methods are gravimetric and are limited to concentrations greater than 0.10 mg/m³.

Diesel particulate measurements were made in coal and non-coal mines using current control technology. For coal mines, diesel particulate levels for face workers ranged from 0.20 mg/m³ to 1.00 mg/m³. Exposure levels on a section varied by +0.20 mg/m³. The samples collected in the haulageway (inby the section dump point) agreed with the personal exposure measurements of the section workers. As air volume increased the diesel particulate levels decreased.

For non-coal mines, diesel particulate levels ranged from 0.30 mg/m³ to 1.50 mg/m³. When series ventilation was used, successively higher diesel particulate levels resulted on downwind working sections. Measurements were uniform throughout a working section. ♦

References

Cantrell, B.K. and Rubow, K.L. 1990. "Development of a personal diesel aerosol sampler - design and performance criteria." SME Annual Meeting, Feb. 26 - March 1, 1990, Salt Lake City, UT.

Haney, R.A. 1989. "Evaluation of personal Diesel particulate samplers." *Proceedings of the 4th US Mine Ventilation Symposium*, Berkeley, CA.

NIOSH, 1988. "Carcinogenic effects of exposure to diesel exhaust." NIOSH Current Intelligence Bulletin 50.

Rubow, K.L., et al., 1988. "Measurement of coal dust and diesel exhaust aerosols," *Proceedings of the VIIth International Pneumoconiosis Conference*, NIOSH, Pittsburgh, Pennsylvania.

US Department of Labor, 1988. "Report of the Mine Safety and Health Administration Advisory Committee on Standards and Regulations for Diesel-Powered Equipment in Underground Coal Mines."